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Radiative flux and forcing parameterization error in aerosol-free clear skies

Robert Pincus[1,2], Eli J. Mlawer[3], Lazaros Oreopoulos[4], Andrew S. Ackerman[5], Sunghye Baek[6,7], Manfred Brath[8], Stefan A. Buehler[8], Karen E. Cady-Pereira[3], Jason N. S. Cole[9], Jean-Louis Dufresne[6], Maxwell Kelley[5,10], Jiangnan Li[9], James Manners[11], David J. Paynter[12], Romain Roehrig[13], Miho Sekiguchi[14], and Daniel M. Schwarzkopf[12]

[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Boulder, Colorado, USA, [2]Physical Sciences Division, NOAA/Earth System Research Lab, Boulder, Colorado, USA, [3]Atmospheric and Environmental Research, Lexington, Massachusetts, USA, [4]Earth Science Division, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, [5]Goddard Institute for Space Studies, New York, New York, USA, [6]CNRS/IPSL/LMD, Université Pierre et Marie Curie, Paris, France, [7]Korea Institute of Atmospheric Prediction Systems, Seoul, Korea, [8]Meteorological Institute, University of Hamburg, Hamburg, Germany, [9]Canadian Center Climate Modelling and Analysis, Environment Canada, Victoria, British Columbia, Canada, [10]Trinnovim LLC, New York, New York, USA, [11]Met Office, Exeter, UK, [12]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA, [13]Centre National de Recherches Météorologiques-GAME, Météo-France and CNRS, Toulouse, France, [14]Department of Marine Electronics and Mechanical Engineering, Tokyo University of Marine Science and Technology, Tokyo, Japan

Key Points:
- Radiation parameterizations in GCMs are more accurate than their predecessors
- Errors in estimates of $4 \times CO_2$ forcing are large, especially for solar radiation
- Errors depend on atmospheric state, so global mean error is unknown

Supporting Information:
- Readme
- Data S1
- Data S2
- Data S3

Correspondence to:
R. Pincus,
Robert.Pincus@colorado.edu

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Abstract This article reports on the accuracy in aerosol- and cloud-free conditions of the radiation parameterizations used in climate models. Accuracy is assessed relative to observationally validated reference models for fluxes under present-day conditions and forcing (flux changes) from quadrupled concentrations of carbon dioxide. Agreement among reference models is typically within 1 W/m^2, while parameterized calculations are roughly half as accurate in the longwave and even less accurate, and more variable, in the shortwave. Absorption of shortwave radiation is underestimated by most parameterizations in the present day and has relatively large errors in forcing. Error in present-day conditions is essentially unrelated to error in forcing calculations. Recent revisions to parameterizations have reduced error in most cases. A dependence on atmospheric conditions, including integrated water vapor, means that global estimates of parameterization error relevant for the radiative forcing of climate change will require much more ambitious calculations.

1. Assessing the Accuracy of Radiation Parameterizations in Climate Models

Radiative transfer is unique among parameterization problems for global atmospheric models because the governing equations are deeply grounded in fundamental physics, the approximations (e.g., of one-dimensional radiative transfer) applicable across many relevant scales, and the result entirely deterministic. In aerosol-free clear skies, where scattering is small relative to absorption and emission, the problem is defined by the profile of extinction of the gaseous atmosphere, which is itself determined by the profiles of temperature, pressure, and the concentrations of radiatively active gases. Fluxes of longwave or terrestrial radiation also depend on how the extinction profile is related to the profile of local emission (which also depends on temperature), while for fluxes of shortwave or solar radiation local emission can be neglected, but Rayleigh scattering, which increases extinction and single-scattering albedo, changes the problem slightly. For monochromatic problems these calculations are straightforward so that the main challenge for atmospheric models is treating the spectral dependence of radiative fluxes.

The best available information for the spectral variation of radiation in the atmosphere comes from so-called line-by-line models with full spectral detail. When the state of the atmosphere is well characterized, such models are now able to match carefully calibrated observations to within fractions of percent at full spectral resolution [see, for example, *Turner et al.*, 2004; *Alvarado et al.*, 2013]. This is sufficiently accurate, for example, that the very small spectrally dependent signal from a decade's increase in CO_2 concentrations can be teased from surface measurements of spectral intensity that are dominated by secular changes in temperature and water vapor [*Feldman et al.*, 2015]. The absolute accuracy of these models in individual cases is difficult to judge because it is quite difficult to separate errors in the characterization of the atmosphere from errors in the

spectral variation of optical thickness (vertically integrated extinction). Estimates from remaining spectrally resolved differences against observations suggest that absolute errors in broadband fluxes (i.e., fluxes integrated over all energy emitted by the Sun or Earth) are no larger than about 1 W/m^2 [*Oreopoulos and Mlawer*, 2010] in the longwave. Comparisons in the shortwave between spectrally resolved measurements and model calculations have been less extensive but suggest that broadband flux errors are somewhat larger.

Broadband fluxes are required by dynamical models of the atmosphere to compute heating and cooling rates within the atmosphere and surface fluxes of energy. The opacity of the cloud- and aerosol-free atmosphere (e.g., the "clear, clean" conditions of *Ghan* [2013]) depends strongly enough on temperature and radiatively active gas concentrations that the extinction of the gaseous atmosphere is computed anew at each location and time. Line-by-line models are impractically slow for this task because absorption coefficients due to gases vary by many orders of magnitude over very narrow spectral intervals. Computationally efficient parameterizations therefore use techniques such as exponential sum fitting of transmissivities [*Hunt and Grant*, 1969; *Wiscombe and Evans*, 1977], correlated *k*-distributions [*Lacis and Oinas*, 1991; *Fu and Liou*, 1992], or the simplified exchange approximation [*Fels and Schwarzkopf*, 1981; *Schwarzkopf and Ramaswamy*, 1999] to approximate the spectral integral using a relatively small number of quadrature points minimizing some measure of error across a distribution of atmospheric states. (Other simplifications frequently used in parameterizations, such as low angular resolution or the neglect of scattering in the longwave, do not introduce significant errors in aerosol-free clear skies.)

Systematic assessments of parameterizations against the reference models on which they are based date back more than two decades [*Ellingson and Fouquart*, 1991; *Cess et al.*, 1993]. Parameterizations have improved over time such that the best now reproduce line-by-line flux calculations in present-day conditions to within about 1 W/m^2 [*Oreopoulos et al.*, 2012], although a surprisingly large range of error still exists for such a well-understood problem. Parameterizations are substantially less accurate with respect to forcing calculations [*Collins et al.*, 2006; *Forster et al.*, 2011] (i.e., the change in flux due to a change in atmospheric composition) in part because the sets of atmospheric states used to develop parameterizations often do not include large variations in composition [see, e.g., *Mlawer et al.*, 1997, section 4].

But changes in radiative flux that arise from increasing levels of greenhouse gases are precisely the radiative forcing that drives climate change. Parameterization errors in estimates of clear-sky instantaneous radiative forcing, a purely radiative quantity that might be determined to high precision, are one reason that different models participating in coordinated experiments (e.g., the Coupled Model Intercomparison Project or CMIP; see *Taylor et al.* [2012], which describes the recently concluded CMIP5) may be subject to different instantaneous forcing for the same change in atmospheric composition [*Zhang and Huang*, 2014; *Chung and Soden*, 2015]. This is especially true for large excursions from present-day conditions such as "$4 \times CO_2$" (carbon dioxide concentrations quadrupled from their preindustrial value). Despite this concern, abrupt $4 \times CO_2$ experiments are widely used to obtain estimates of sensitivity and effective radiative forcing from time-evolving flux imbalance and temperature [*Gregory et al.*, 2004].

Here we examine the accuracy of the greenhouse gas component of a set of parameterizations used in atmospheric models. We consider both fluxes under a range of present-day conditions and the forcing from quadrupled concentrations of carbon dioxide under the same range of conditions. We focus on parameterizations used in climate models (roughly, those that participate in CMIP experiments) because these models are often used to understand the response to forcing; here we seek to identify errors in the forcing itself. (Similar assessments by the chemistry-climate [*Forster et al.*, 2011] and aerosol [*Randles et al.*, 2013] communities have focused on more process-specific metrics using a different set of models though with broadly similar results.) We demonstrate below that recent revisions to parameterizations at several modeling centers have reduced error (at least in our test cases) but that errors in absorption relative to surface and top-of-atmosphere fluxes imply biases in present-day model hydrologic cycles and in the hydrologic sensitivity to increasing greenhouse gas concentrations. We also show that parameterization accuracy often depends on atmospheric state and composition, suggesting that estimates of accuracy at the global scales needed to estimate radiative forcing error require large-scale assessments across a wide-ranging set of conditions.

2. Building on Previous Assessments

We report on calculations following a variant of the protocol used by the First Phase of the Continual Intercomparison of Radiation Codes (CIRC) [see *Oreopoulos et al.*, 2012] in which broadband fluxes are computed

for atmospheric and surface conditions (temperature, pressure, and greenhouse gas concentrations) specified in between 55 and 66 layers, roughly comparable to the vertical resolutions used in climate models. In most cases participants performed the calculations with radiative transfer codes extracted from the host model (see the recommendation by *Forster et al.* [2011]), although at least one implemented diagnostic calculations in a single-column version of the full model. We focus on the treatment of gases by considering four clear-sky cases, with precipitable water vapor ranging from 0.32 to 4.85 cm, originally chosen for good agreement between spectral measurements at the surface and reference model calculations using estimates of the overlying atmospheric state. We further simplify the problem by specifying no aerosols and spectrally uniform surface albedo and emissivity. We perform two sets of experiments, one under the initially observed atmospheric conditions (essentially repeating the shortwave "case b" calculations of *Oreopoulos et al.* [2012]) and a second in which the observed concentrations of CO_2 have been quadrupled. Fluxes are reported at the top of atmosphere and the surface. Atmospheric absorption or emission (radiative divergence) is computed as the difference between net downward radiation at these two levels. Forcing is the difference between $4 \times CO_2$ and present-day conditions.

We solicited contributions from modeling centers that participate in CMIP exercises. Many provided results from the current version of their radiation parameterization; some also provided results from the version used in CMIP5 [*Taylor et al.*, 2012]. Calculations made with version 12.2 of the Line-By-Line Radiative Transfer Model (LBLRTM) model [*Clough et al.*, 2005] provide the benchmark, as they did for CIRC (though CIRC used a slightly older version). Participating radiation models and results from LBLRTM are detailed in the supporting information. Although our assessment does not include every parameterization used by models participating in CMIP, several parameterizations are used in more than one model, so that the radiation component is even less diverse than the already interdependent set of models itself [*Knutti et al.*, 2013].

3. Results From CMIP5 and Beyond

As with past assessments, we find that reference models agree with one another to within 1 W/m^2, or to fractions of a percent, for almost all calculations, though this level of agreement is not a measure of uncertainty. The absolute accuracy of line-by-line models, as measured by comparisons of high-resolution spectra against observations [e.g., *Delamere et al.*, 2010; *Mlawer et al.*, 2012; *Alvarado et al.*, 2013], is improving over time. In most cases improvements are due to refined information about the presence, position, and strength of individual absorption lines or continua. Better spectral information introduces changes in broadband fluxes, illustrated in Figure 1 by results from an older version (9.4+) of LBLRTM (orange squares in this and all subsequent figures) which has less complete spectroscopy and different models for the water vapor continuum, and agrees less well with spectrally resolved observations, than the more recent version (12.2) we use as our benchmark. (Broadband fluxes and forcings are far more similar than spectrally resolved differences; see *Alvarado et al.* [2013].) More sophisticated treatment of line interactions is also useful: the primary difference between the ARTS 2.2 (small black squares) and ARTS 2.3 (large black squares) is the treatment of line mixing by CO_2 (revisions to continua, also present, have a small impact). Full names of the radiative transfer codes and the institutions using them is provided in the supporting information.

Nonetheless, line-by-line model results are almost entirely determined by the underlying spectroscopic data including models for absorption continua. All the line-by-line models in this study use the same continua in the longwave, so spread among the reference models does not reflect true uncertainty. Indeed, line-by-line models have agreed well with one another for several decades [e.g., *Ridgway and Arking*, 1991], often to a greater degree than they have agreed with observations.

Whatever the underlying uncertainty in line-by-line calculations, parameterizations are constructed to reproduce these reference model results across a range of atmospheric conditions. By this measure parameterization accuracies vary more widely across quantities (e.g., top-of-atmosphere versus surface flux), spectral intervals, and atmospheric conditions than do reference models. For top-of-atmosphere longwave flux and forcing, as one example, parameterization error is relatively low (Figure 1) [see also *Oreopoulos et al.*, 2012], but even here errors of 2 W/m^2 (roughly 1%, depending on the case) in present-day net flux and 0.5 W/m^2 (10%) in forcing from quadrupled CO_2 concentrations are common. Figure 1 is meant to be illustrative; readers interested in details will find an exhaustive set of figures in the supporting information.

Revisions to parameterizations since CMIP5 have reduced errors, in some cases dramatically, with respect to both flux and forcing (compare the filled circles and dark grey histogram bars in Figure 1 to the open circles and

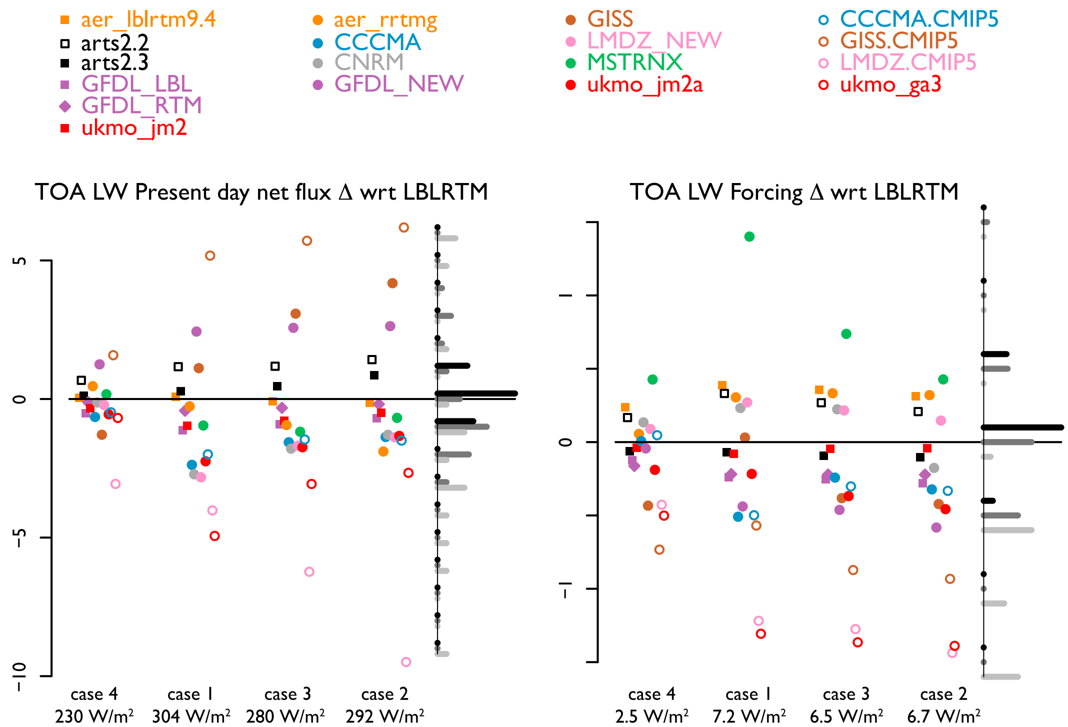

Figure 1. (left) Errors in top-of-atmosphere net downward broadband longwave flux under present-day conditions and (right) error in forcing from CO_2 concentrations quadrupled from present-day values for a variety of reference models (squares, including one high-resolution *k*-distribution model) and parameterizations used in climate models (circles). Calculations for four atmospheric profiles are ordered by column-integrated water vapor ranging from 0.32 to 4.85 cm. Reference values are noted. Histograms along the right edge of each panel show the error by model type (black for reference models, dark grey for current parameterizations, and light grey for parameterizations used in CMIP5; normalized across model categories) in intervals of 1 (Figure 1, left) or 0.5 (Figure 1, right) W/m^2) centered on 0. Reference models agree to within fractions of a percent in most calculations. Parameterization error is larger but still modest, with error in some parameterizations depending strongly on the water vapor path. Parameterizations that have been updated since CMIP5 are more accurate than their predecessors (compare filled circles and dark grey histogram bars to open circles and light grey bars.)

light grey histogram bars; see also Figures S1 and S2 in the supporting information). In most cases the reduced error is due to improved parameterizations of spectroscopy, i.e., more accurate treatment of how the optical thickness of the gaseous component of the atmosphere depends on temperature, pressure, and composition. (Other changes may be relevant for more complicated atmospheric conditions including aerosols and clouds.)

The remaining error is not random, however. Many parameterizations systematically either overestimate or underestimate a given radiative quantity. Perhaps more importantly, errors depend to some extent on atmospheric state including the profile of temperature and humidity. This is evident in how the error in present-day flux in the GISS parameterizations (shown in brown circles), and the error in forcing in all models but especially MSTRNX (green circles), depend on column-integrated water vapor, which increases from left to right in Figure 1. As we discuss below, the state dependence of parameterization error makes it hard to extrapolate from relatively few cases, even those constructed to sample, say, latitudinal dependence [*Myhre and Stordal*, 1997; *Forster et al.*, 2011] to global or regional estimates of error.

Relationships among errors at the top of atmosphere, surface, and within the atmosphere can have important impacts on the host model: because globally averaged surface radiative fluxes affect the planet's surface temperature while net radiative cooling controls the global amount of precipitation, radiation parameterization errors can impact present-day energy and water cycles nearly independently. In general, errors in longwave fluxes at the top-of-atmosphere and surface often partially compensate for one another (Figure 2, left). For some parameterizations the reasons for this compensation are understood: the GFDL longwave parameterization, for example, includes energy in a narrower spectral interval than do the reference calculations, resulting

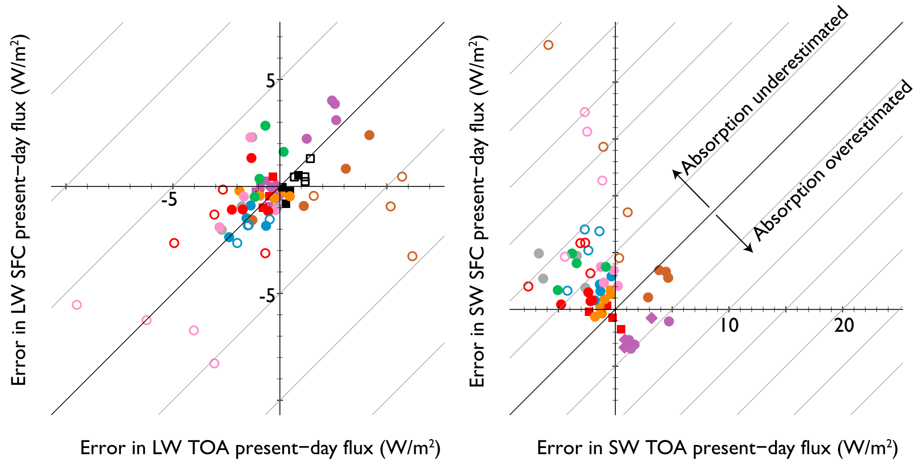

Figure 2. Errors in surface net downward (left) longwave and (right) shortwave flux in the present day as a function of errors in net top-of-atmosphere flux, along with (diagonal) isolines of constant error in atmospheric absorption inferred from fluxes at the boundary. All four cases are shown. Axis tick marks are every 1 W/m^2 and absorption isolines every 5 W/m^2. Errors in longwave boundary fluxes and radiative divergence are generally within a few W/m^2, especially for current parameterizations, while errors in shortwave fluxes and absorption are twice as large.

in smaller upwelling fluxes (positive error) at both the surface and top of the atmosphere and hence very small impacts on atmospheric cooling.

Calculations in the shortwave are generally less accurate in absolute terms than in the longwave [see also *Oreopoulos et al.*, 2012], though for boundary fluxes the relative errors are similar (within a few percent). More importantly, shortwave errors at the top of atmosphere tend to be of opposite sign to those at the surface, leading to errors in radiative divergence as large as 10 W/m^2 or 5% even for current parameterizations. Errors for the GISS and LMDZ CMIP5-era parameterizations are even more dramatic. In all but one parameterization shortwave absorption tends to be underestimated, implying a bias toward increased global precipitation in many host models. The exception is the GFDL parameterization, for which slightly greater solar absorption is consistent with the reference model on which the parameterization is based. This line-by-line model absorbs more than our benchmark due to more recent underlying spectroscopic data and to a different treatment of water vapor continua due to *Paynter and Ramaswamy* [2011]. Thus, the overestimate of absorption by GFDL relative to our reference is more properly viewed as a legitimate difference than an error.

Similarly, the partitioning of forcing errors within and at the boundaries of the atmosphere means that parameterization errors may project differently onto climate (temperature) and hydrologic sensitivities to increasing concentrations of greenhouse gases. In the shortwave most 4 × CO_2 forcing errors, like errors in present-day fluxes, are of opposite sign at the boundaries (see Figure 3, left) so that errors in radiative divergence are relatively larger than at the surface or the top of the atmosphere. This implies that radiation parameterization errors will have larger impacts on hydrologic sensitivity than on climate sensitivity. The situation is much better in the longwave as shown in Figure S3. In practice relationships between forcing at the boundaries of and within the atmosphere will be modified by tropospheric and stratospheric adjustments, normally considered as part of the total forcing, that may dampen or amplify one error without affecting others.

It is tempting to think of parameterizations as being better or worse depending on some measure of the error in, for example, present-day fluxes, but the size of the error under present-day conditions says nearly nothing about the magnitude of errors in forcing (Figures 3, right, and S4). Instead, relationships between errors in present-day and 4 × CO_2 conditions are determined more by the parameterization being used than by atmospheric state. To the extent that these results hold on a global scale, it suggests both that present-day biases do not imply errors in forcing (e.g., the Met Office or GFDL parameterizations) and, conversely, that parameterizations with small errors in the present day may still have significant forcing errors (e.g., the CCC and RRTMG parameterizations).

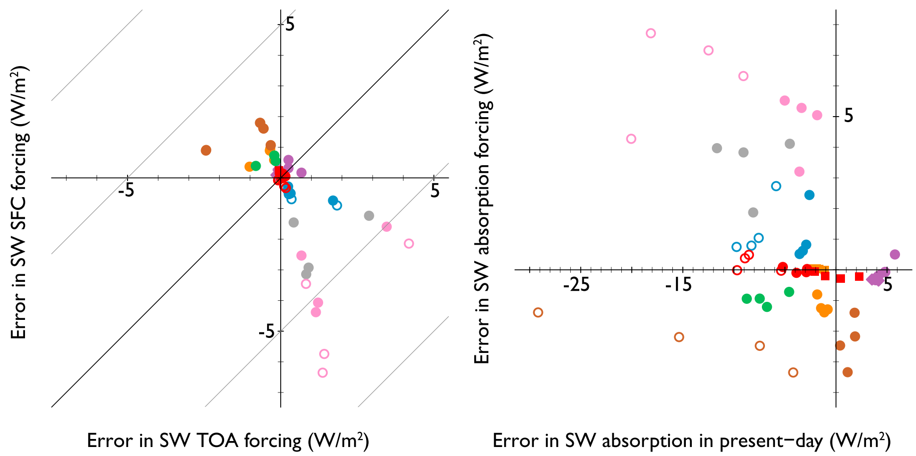

Figure 3. (left) Errors in surface net downward shortwave forcing from quadrupled present-day CO_2 concentrations as a function of error in net top-of-atmosphere forcing, along with (diagonal) isolines of constant error in atmospheric absorption forcing. Axis tick marks are every 1 W/m^2 and absorption isolines every 5 W/m^2. For many parameterizations errors in top-of-atmosphere forcing are smaller than errors in surface forcing, implying errors in absorption forcing with impacts on the host model's hydrologic cycle. (right) Error in solar absorption forcing as a function of error in the present-day estimates of solar absorption. Parameterizations have characteristic relationships among present-day and forcing errors that outweigh the impact of atmospheric state. Errors in the present day are a poor predictor of errors in forcing.

4. Tracing Error From a Few Aerosol-Free Clear Skies to Projections of Climate Change

A focus on clear skies may seem narrow given that roughly two thirds of the planet's surface at any given time is covered by some kind of cloud [e.g., *Stubenrauch et al.*, 2013]. But clear-sky errors exist even in cloudy skies (though they need not add linearly to errors introduced in the treatment of clouds), and clouds do not affect forcing directly, so that characterizing the error in aerosol-free clear skies remains a useful starting point for assessing errors in radiative forcing.

The errors reported here come from snapshots at an essentially arbitrary point in time. In particular, the models to be used in CMIP6 [*Meehl et al.*, 2014] are still under construction and the radiation parameterizations are subject to revision before simulations are made and shared. One goal of intercomparison exercises is to identify errors so they may be fixed (see discussions in *Cahalan et al.* [2005], for example), and this study has already motivated two changes reflected in our results: spectroscopy was updated in the GISS parameterizations, and an important simplification (the assumption that surface skin and surface air temperature are identical) was relaxed in the LMDZ and CNRM longwave parameterizations after initial calculations demonstrated relatively large errors in two cases. Further revisions may be expected in the next generation of climate models. Some, we hope, will expand the range of atmospheres used to train the parameterization to include conditions such as large concentrations of greenhouse gases.

The reference models on which radiation parameterizations are based are themselves moving targets whose results change modestly as knowledge of the underlying spectroscopy improves, especially in the shortwave. All reference models in this study, for example, rely on the HITRAN (HIgh-resolution TRANsmission) spectroscopic data; differences between the 2012 and 2008 versions [*Rothman et al.*, 2009, 2013] explain half or more (1 to 1.5 W/m^2, depending on the case) of the difference in absorption calculations with LBLRTM (which uses the older version) and the GFDL RFM line-by-line model. Periodic and/or continual assessments of radiation parameterizations help modeling centers from straying too far from current spectroscopic knowledge.

Radiation parameterization error is a function of the state of the atmosphere, as is clear from Figure 1. The set of conditions used in our calculations was originally determined by the availability of high-quality observational data with which line-by-line models could be validated [*Turner et al.*, 2004]. We cannot extrapolate from these limited results to obtain global estimates of parameterization error in even in aerosol- and cloud-free skies. One goal of the Radiative Forcing Model Intercomparison Project (RFMIP, http://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/modelling-wgcm-mips/418-wgcm-rfmip)

associated with CMIP6 is to provide such globally relevant estimates, under present-day and future conditions and in strongly forced scenarios, by performing off-line radiative transfer calculations under a much larger range of atmospheric conditions than is discussed here or in past assessments — a set of conditions designed to allow for estimates of global parameterization error. These calculations will enable the surprisingly large diversity in instantaneous clear-sky radiative forcing from $4 \times CO_2$ [*Zhang and Huang*, 2014; *Chung and Soden*, 2015], for example, to be decomposed into correctable parameterization errors and legitimate differences in model climatology.

Highly accurate calculation of radiative fluxes is of primary interest to the climate modeling community where long free-running simulations and highly variable greenhouse gas concentrations are the norm. The range of parameterization errors, especially with respect to forcing, implies that specifying changes in greenhouse gas concentrations (as in CMIP) does not completely determine the instantaneous clear-sky radiative forcing to which each model is subject. In fairness it is the effective radiative forcing, including model-specific rapid adjustments [see, e.g., *Sherwood et al.*, 2015] and state-dependent sensitivities, that is relevant to determining the long-term climate response. Diversity in adjustments [*Andrews et al.*, 2012; *Zelinka et al.*, 2014] will partly mask and may well outweigh the range of parameterization error. But rapid adjustments themselves can be influenced by radiation parameterization error [*Ogura et al.*, 2014], and, given the maturity of understanding about radiative transfer, global estimates of parameterization error are a necessary first step in efforts to characterize and assess radiative forcing.

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Erratum

In the originally published version of this article, the Supporting Information was incorrectly formatted. The errors have since been corrected, and this version may be considered the authoritative version of record.